GER-4001

A New Magnetizing Inrush Restraining Algorithm for Power Transformer Protection

NEW MAGNETIZING INRUSH RESTRAINING ALGORITHM FOR POWER TRANSFORMER PROTECTION

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INTRODUCTION

Large power transformers belong to a class of vital and very expensive components in electric power systems. Accordingly, high demands are imposed on power transformer protective relays. The operating conditions of transformer protection, however, do not make the relaying task easy. Protection of large power transformers is one of the most challenging problems in the area of power system relaying.

Magnetizing inrush inhibit is one the issues. Traditional second harmonic restraining technique may face security problems as the level of the second harmonic may drop below the reasonable threshold setting (around 20%) permanently or for several power system cycles during magnetizing inrush conditions. This is particularly true for modern transformers with magnetic cores built with improved materials, but it has a bearing upon old designs as well [1].

Numerical relays capable of performing sophisticated signal processing functions enable the relay designer to re-visit the classical protection principles and enhance the relay performance, facilitating faster, more secure and dependable protection for power transformers [2,3].

A new magnetizing inrush restraining technique presented in this paper uses the angular relationship between the first and second harmonics of the differential current. Thus, the technique adds a new dimension to the traditional approach that measures the magnitude ratio only between the fundamental frequency component and the second harmonic.

MAGNETIZING INRUSH

Magnetizing inrush currents in power transformers results from any abrupt change of the magnetizing voltage. Although usually considered a result of energizing a transformer, the magnetizing inrush may be also caused by:

(a) occurrence of an external fault,
(b) voltage recovery after clearing an external fault,
(c) change of the character of an external fault, and
(d) out-of-phase synchronizing of a near-by generator.

Since the magnetizing branch representing the core appears as a shunt element in the transformer equivalent circuit, the magnetizing current upsets the balance between the currents at the transformer terminals, and is therefore experienced by the differential relay as a "false" differential current.

Inrush due to switching-on

Initial magnetizing due to switching a transformer on is considered the most severe case of an inrush. When a transformer is de-energized, the magnetizing voltage is taken away, the magnetizing current goes to zero while the flux follows the hysteresis loop of the core. This results in certain remanent flux left in the core. When, afterwards, the transformer is re-energized by an alternating sinusoidal voltage the flux gets biased by the remanence. The residual flux may be as high as 80-90% of the rated value [1], and therefore, it may shift the flux-current trajectories far above the knee-point of the characteristic resulting in both large peak values and heavy distortions of the magnetizing current.

Figure 1a shows a sample inrush current. The waveform displays a large and long lasting dc component, is rich in harmonics, assumes large peak values at the beginning, decays substantially after a few tenths of a second, but its full decay occurs only after several seconds.

The shape, magnitude and duration of the inrush current depend on several factors. They are [1]:

(a) Size of a transformer.
(b) Impedance of the energizing system.
(c) Magnetic properties and remanence of the core.
(d) Point-on-wave (phase angle) and way (inner, outer winding, type of switchgear) the transformer is switched on.

Harmonic content of the inrush current

Assume the analytical approximation shown in Figure 2 for calculation of the frequency spectrum of the inrush current. The angle a is a parameter facilitating modeling of an actual inrush current. For example, during first few cycles of the waveform of Figure 1a the angle is quite small, while from the 10^{th} cycle on, the angle becomes quite large.

The amplitude of the *n*-th harmonic of the waveform of Figure 2 is calculated as:

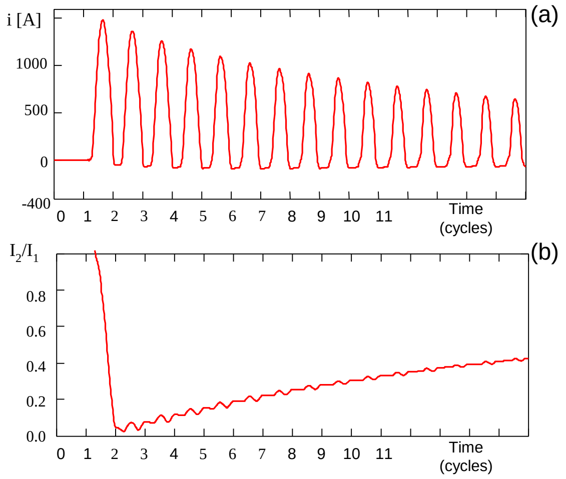

Figure 1: Sample inrush current (a) and its second harmonic ratio (b).

$$A_n = \frac{I_m}{p}\left[\frac{1}{n+1}\sin\left((n+1)a\right)+\frac{1}{n-1}\sin\left((n-1)a\right)-2\cos\left(\frac{a}{n}\right)\sin\left(na\right)\right] \quad (1)$$

Figure 3 presents the frequency spectrum of the signal shown in Figure 2 calculated with the use of (1) for a =60, 90 and 120 degrees, respectively. As seen from the figure, the second harmonic always dominates because of a large dc component. However, the amount of the second harmonic may drop below 20%. The minimum content of the second harmonic depends mainly on the knee-point of the magnetizing characteristic of the core. The lower the saturation flux density, the higher the amount of the second harmonic.

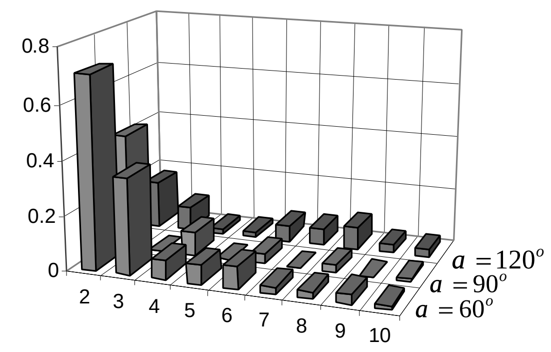

Figure 3: Harmonic content of the idealized inrush current of Figure 2 for a = 60, 90 and 120 degrees.

INRUSH RESTRAINT METHODS

Modern means of restraining differential relays during magnetizing inrush conditions recognize the inrush pattern in the differential current either indirectly (harmonic analysis) or directly (waveform analysis) [2].

Harmonic restraint

This is a classical way to restrain the relay from tripping during magnetizing inrush conditions. The magnetizing inrush current appearing to a relay as the differential signal displays high amounts of higher harmonics. Generally, low levels of harmonics enable tripping, while high levels indicate inrush and restrain the relay. For digital relays this may be written as:

$$TP = I_{CH} < \Delta\, I_{CD} \quad (2)$$

where:

TP	Tripping Permission from the inrush detector,
I_{CH}	Combined Harmonic component in the differential current,
I_{CD}	Combined Differential current,
Δ	threshold.

The condition (2) originates a whole family of algorithms using a variety of approaches in combining currents I_{CH} and I_{CD}.

In the simplest approach, the amplitude of the second harmonic in the differential current in a given phase is the combined harmonic signal, while the amplitude of the fundamental frequency component in the differential current in the same phase is used as the combined differential current:

$$\left.\begin{aligned} I_{CH} &= I_{D2\,phase} \\ I_{CD} &= I_{D1\,phase} \end{aligned}\right\} \quad (3)$$

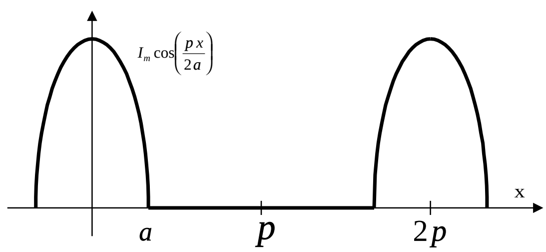

Figure 2: Idealized inrush current.

The harmonic restraint in general, regardless of the method of composing the combined harmonic and differential signals, displays certain limitations. In modern transformers the amount of higher harmonics in the magnetizing current may drop well below 10% (the second harmonic as low as 7%, while the total harmonic content at a level of 7.5% [1]). Under such circumstances (see Figure 1 for example), the setting *D* in (2) should be adjusted at a very low value. This may lead, however, to delayed or even missing operation of the relay due to the harmonics in the differential currents during internal faults accompanied by saturation of the CTs. Cross-restraint or time-controlled threshold provide only a partial solution to this problem [2,3].

Other approaches

Other approaches include:

- Waveform-based algorithms [2].
- Model methods [4,5].
- Differential power method [6].
- Flux-based method [7].

They do not address the problem entirely.

NEW ALGORITHM

The classical second harmonic restraint compares the magnitude of the second harmonic with the magnitude of the fundamental frequency component. Following this traditional approach one neglects the other dimension of the derived ratio — the phase relation.

Figure 4 presents an idealized magnetizing inrush current of Figure 2 with its fundamental frequency component and the second harmonic superimposed. Because the waveform is symmetrical the first and second harmonics are “in phase” as their signal models have the same initial angle.

In terms of rotating phasors, however, there are problems in defining the phase angle between the fundamental frequency component and the second harmonic. As the second harmonic rotates twice as fast as the fundamental frequency phasor the phase angle between the second and first harmonics varies cyclically. This obsta-

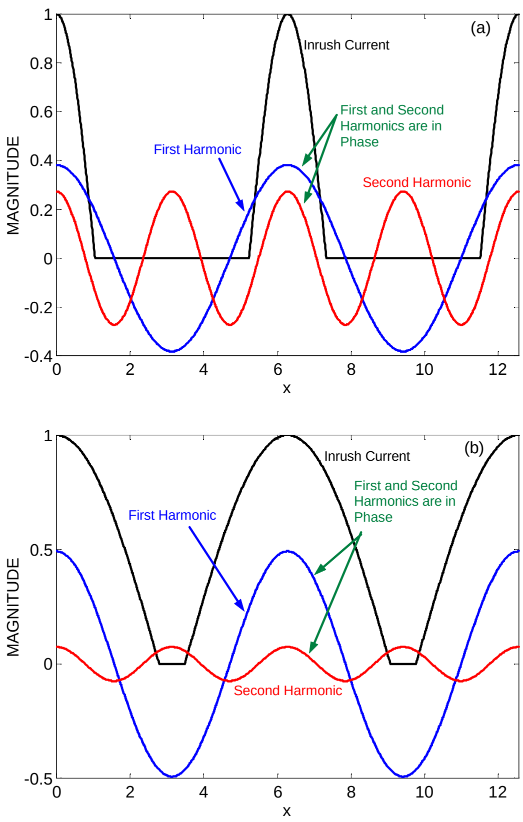

Figure 4: The first and second harmonics are "in phase" during inrush conditions. Large (a) and small (b) second harmonic ratio situations.

cle has been overcome by introducing the following two-dimensional (complex) second harmonic ratio:

$$I_{21} = \left|\frac{I^{2nd}_{DIFF}}{I^{1st}_{DIFF}}\right| \angle\, angle\left(I^{2nd}_{DIFF}\right) - 2 \cdot angle\left(I^{1st}_{DIFF}\right) \qquad (4)$$

where all the involved currents are rotating vectors.

Depending on the definition of the phasors, the attribute of the fundamental frequency component and the second harmonic being "in phase" during inrush conditions should be understood as follows:

(a) If the cosine function is a base for the real part of the phasor, then the angle between the first and second harmonics is 0 or 180 degrees during inrush conditions.

(b) If the sine function is a base for the real part of the phasor, then the angle between the first and second harmonics is either +90 degrees or –90 degrees during inrush conditions.

In this paper, convention (b) is followed.

Analysis similar to the one depicted in Figure 4 has been carried out for the waveform model that included a decaying dc component with the time constant varied over a wide range. Again, an analytical proof has been obtained that the phase angle difference between the second and first harmonics defined as (b) above is close to ±90 degrees regardless of the ratio of amplitudes.

Statistical evaluation of the new principle

The algorithm has been tested using numerous waveforms obtained by simulation and from recordings on physical made-to-scale transformers.

The following factors ensure diversity of the considered cases:

- both wye-delta and wye-wye connections have been taken into account,
- energization from both wye and delta windings has been considered,
- energization onto an internal fault has been considered,
- variety of inrush factors have been taken into account (weak and strong energizing systems, random residual magnetism, random point-on-wave when energizing, etc.).

The performed analysis has showed improved discrimination ability of the new algorithm comparing with the traditional second harmonic restraint.

To illustrate this, Figure 5a presents a histogram of the complex second harmonic ratio for internal faults in wye-wye and delta-wye transformers. The new restraint quantity converges at the origin. The values away from the origin are marginal and are distributed quite uniformly.

For comparison, Figure 5b shows a histogram of the new decision signal for numerous inrush cases for energizing from both wye and delta windings. As seen from

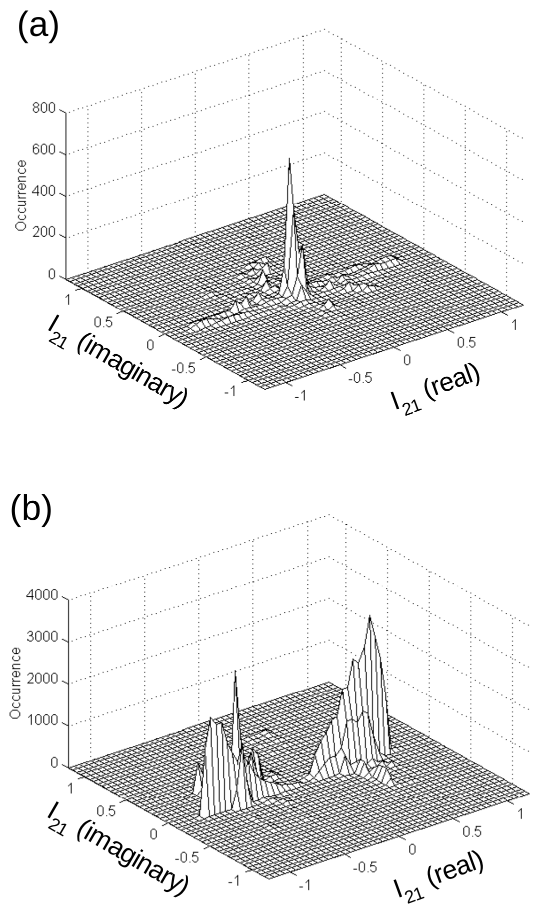

Figure 5: Internal fault (a) and inrush (b) patterns.

the figure, the values of the complex second harmonic ratio cluster along the ±90-degree lines

Thus, there is significant separation between the internal fault (Figure 5a) and inrush (Figure 5b) patterns. This ensures robust operation of the new algorithm.

Operate/Restraint regions

Taking the statistical difference of Figure 5 into account the operating region for the new decision quantity $\underline{I}_{21}$ has been shaped as shown in Figure 6.

The following applies to the operate/restraint regions (Figure 6):

- the operating region stretches between approximately ±20% for angles close to 0 and 180 degrees (traditional second harmonic restraint),
- for angles close to ±90 degrees the operating region is cut with two lens-like shapes ensuring blocking for low values of the second harmonic,
- the lens-like cut-offs are not stationary, but are made functions of time — initially, the cut-offs are very deep, but after several cycles they disappear leaving a classical circular-like operating characteristic.

As a result of the dynamic restraint, one obtains a time-dependent operating characteristic for the complex second harmonic ratio. The time required to unblock the relay (i.e. the time after which the magnetizing inrush restraint is taken out) is a function of $\underline{I}_{21}$. If the latter does not change in time, the stationary t–$\underline{I}_{21}$ relation may be derived as shown in Figure 7. The obtained characteristic has the following distinctive features:

- if the angle of $\underline{I}_{21}$ is close to 0 or 180 degrees, the inrush restraint is removed immediately regardless of the magnitude of the second harmonic,
- if the angle is close to ±90 degrees the delay before removing the restraint depends on the amount of the second harmonic: for low ratios of the second harmonic, the delay is very short; while for ratios close to 20% is rises to 5-6 cycles; this is enough to prevent maloperation due to low values of the second harmonic during inrush conditions.

CONCLUSIONS

This paper presents a new inrush restraint algorithm for protection of power transformers. The algorithm is an extension of the traditional second harmonic method — instead of measuring the ratio between the magnitudes of the second harmonic and the fundamental frequency component – the algorithm considers a ratio between the phasors of the second and the fundamental frequency components of the differential signal.

The new decision signal has been proposed together with the appropriate operating region. The operating region is made dynamic in order to maximize the relay performance on internal faults.

The new algorithm has been successfully implemented using the universal relay platform [8].

The results of extensive testing prove that the algorithm enhances the relay stability during magnetizing inrush conditions maintaining – at the same time – excellent performance on internal faults.

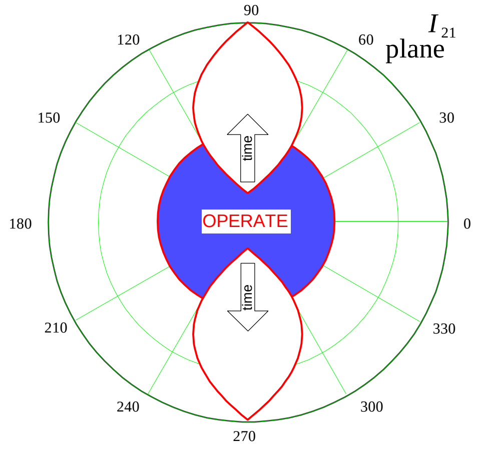

Figure 6: Operating characteristic for the new decision quantity.

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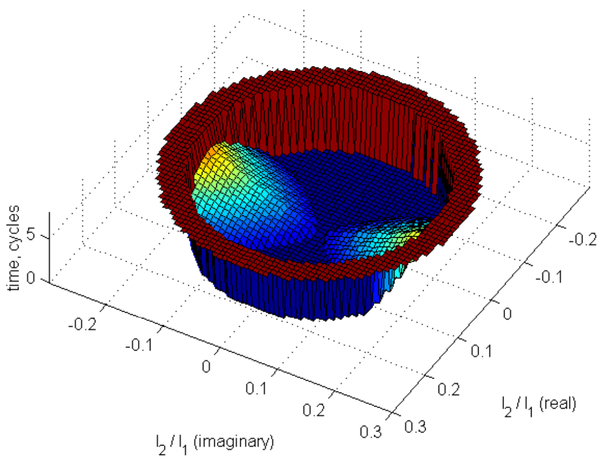

Figure 7: Effective operating characteristic (t–$\underline{I}_{21}$) for the complex second harmonic restraint.